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Delayed disengagement of attention from distractors signalling reward

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ABSTRACT

Attention refers to the set of cognitive mechanisms that facilitate the prioritization of incoming sensory information. Existing research suggests that motivationally salient stimuli, such as those associated with reward, are prioritized by the attention system and that this prioritization occurs independently of an observer's goals. Specifically, studies of visual search have shown that stimuli signalling the availability of monetary reward are more likely to capture eye movements, even when participants are motivated to ignore such stimuli. In the current study we ask whether reward magnitude influences only the likelihood that stimuli will *capture* spatial attention, or whether reward also influences the ease with which people can *disengage* attention from a location when they are motivated to move their attention elsewhere. Three experiments examined the time taken to disengage from a centrally presented distractor that signalled the availability of high or low reward. We found that participants took longer to move their eyes away from a high-reward distractor, even though this came at financial cost (Experiment 1), that participants were unable to suppress a high-reward distractor consistently presented at the central location (Experiment 2), that slower responding was not due to behavioural freezing in the presence of a signal of high reward (Experiment 3), and that slower responding persisted even when rewards were no longer available (Experiment 4). These results indicate that reward modulates attentional disengagement: signals of high reward hold attention for longer, even when this is counterproductive for performance of ongoing tasks. Our findings further highlight the role of reward in the conflict between automatic and goal-directed attentional processing.

1. Introduction

Attention refers to the set of cognitive mechanisms that act to select and prioritize certain pieces of sensory information from the environment for further processing and action. It is well established that this prioritization can be influenced by our goals (other things being equal, we will preferentially attend to task-relevant stimuli: Egeth & Yantis, 1997; Noudoost, Chang, Steinmetz, & Moore, 2010) and also by the physical features of stimuli (our attention can be captured by stimuli that are distinct in terms of their colour, luminance, onset etc, even when these stimuli are task-irrelevant: Theeuwes, 1992; Theeuwes, Kramer, Hahn, & Irwin, 1998). Notably, more recent research has demonstrated that attention is also fundamentally influenced by our previous experiences with stimuli, and in particular by previous learning about how stimuli relate to motivationally significant events such as rewards and punishments (see reviews: Anderson, 2016; Failing & Theeuwes, 2018; Le Pelley, Mitchell, Beesley, George, & Wills, 2016; Watson, Pearson, Chow et al., 2019; Watson, Pearson, Wiers, & Le Pelley, 2019).

The influence of reward on attention has been demonstrated using a range of procedures testing both spatial attention (e.g., Anderson, Laurent, & Yantis, 2011; Hickey, Chelazzi, & Theeuwes, 2010; Kiss, Driver, & Eimer, 2009) and non-spatial attention (e.g., Le Pelley, Seabrooke, Kennedy, Pearson, & Most, 2017; Raymond & O'Brien, 2009). In the current study, we used a variant of a procedure developed by Le Pelley, Pearson, Griffiths, & Beesley, 2015. This procedure used eye-tracking, which provides a useful online measure of spatial attention since an eye movement (saccade) to a given location is always preceded by a shift of attention to that location (Deubel & Schneider, 1996). Le Pelley et al. used an additional singleton task (Theeuwes, 1991, 1992) in which, on each trial, participants performed a visual search for a diamond target among circles. Critically, one of the circles in the display was a colour-singleton distractor, and the colour of this distractor signalled the magnitude of monetary reward that was available for making a rapid response (an eye movement to the diamond target). Notably, participants were more likely to make an erroneous saccade to the coloured distractor (rather than to the target) when it was rendered in a colour that signalled the availability of high reward

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versus low reward, even though looking at this reward-signalling distractor was counterproductive and resulted in omission of the reward that would otherwise have been earned (see also: Albertella et al., 2017; Failing, Nissens, Pearson, Le Pelley, & Theeuwes, 2015; Le Pelley et al., 2015; Pearson, Donkin, Tran, Most, & Le Pelley, 2015, 2016). That is, participants showed an attentional bias towards the high-reward-signalling distractor, even though this meant they were more likely to lose out on high rewards and hence was contrary to their goal of maximizing reward. This finding of a reward-related attentional bias (Anderson, 2016; Failing & Theeuwes, 2018; Le Pelley et al., 2016; Watson, Pearson, Wiers et al., 2019), has been taken to suggest that reward learning influences the likelihood that stimuli will capture spatial attention. On this account, attention is more likely to be deployed to the location of a high-reward stimulus than a low-reward stimulus, even when this conflicts with the observer's goals.

Performance impairments caused by salient distractors may not only be a consequence of influences on *capture* of spatial attention, however – they may also result from effects on *disengagement* of attention (Born, Kerzel, & Theeuwes, 2011; Posner & Petersen, 1990; Posner, Inhoff, Friedrich, & Cohen, 1987; Wang, Samara, & Theeuwes, 2019). If attention is captured to the location of a salient distractor, disengagement from that distractor is required before attention can shift to the search target. In the context of reward-related stimuli, this raises the possibility that in addition to reward influencing the likelihood that stimuli will *capture* spatial attention, it might also influence the difficulty and speed of disengaging attention from a stimulus location.

Disentangling effects of a manipulation (such as reward) on attentional capture from effects on disengagement is not trivial (Clarke, MacLeod, & Guastella, 2013; Godijn & Theeuwes, 2002). In the case of attentional bias for reward, we are aware of two existing approaches. The first of these approaches used gaze dwell time as a measure of (dis) engagement in the type of visual search task with reward-related stimuli described above (Le Pelley et al., 2015; Theeuwes & Belopolsky, 2012). Specifically, these studies analysed the duration for which gaze dwelled on the reward-signalling distractor (on the subset of trials in which this distractor captured gaze). Neither study found that this dwell duration was significantly influenced by the size of reward signalled by the distractor. This could be taken as evidence against the idea that reward leads to delayed disengagement. However, drawing this conclusion requires accepting the null hypothesis – and notably the measure of disengagement in these studies is likely to be quite insensitive, for two reasons. First, there was only a relatively small subset of trials on which gaze was captured by the distractor, and hence on which distractor dwell duration could be measured (less than 10% of trials for the low-reward distractor in Le Pelley et al.'s study), meaning that estimates were likely to be noisy. And second, corrective saccades (to the target) may be prepared in parallel with the initial (capture) saccade to the distractor (Born et al., 2011; Godijn & Theeuwes, 2002), such that subtle effects of reward on disengagement might have been masked.

The second approach to studying the effect of reward on attentional disengagement has used a modified version of the dot probe task (Müller, Rothermund, & Wentura, 2016). In this task, two 'cue' stimuli appeared simultaneously, quickly followed by a target which appeared in the location of one of these stimuli. Müller et al. found that responses to the target were slower on *invalid* trials (in which the cue display featured a reward-related cue and a neutral [non-reward] cue, and the target subsequently appeared in the location of the neutral cue) than on *neutral-baseline* trials (in which the cue display featured two neutral cues, and the target appeared randomly in the location of one of them). This pattern is consistent with the idea of delayed disengagement from the reward-related cue. Alternatively, however, the finding could reflect an influence of reward on capture rather than disengagement. If reward cues are more likely to capture attention than neutral cues, then on invalid trials attention is more likely to be at the 'incorrect' location when the target appears (since this is the location of the reward cue), whereas on baseline trials attention is equally likely to be at the correct or incorrect location (since both cues are identical on these trials). The response-time cost on invalid trials could then reflect the fact that attention is less likely to be in the location of the target when it appears on invalid trials than identical-cue trials – even if the time required for attention to disengage from reward-related versus neutral cues is similar.

The pattern of slower responding on invalid trials than neutral-baseline trials in Müller et al.'s (2016) study could reflect delayed disengagement from, or enhanced capture by, reward cues. A further aspect of Müller et al.'s findings seems—at first glance—to provide evidence against the explanation in terms of capture. Specifically, participants did not show significantly faster responding on *valid* trials (in which the cue display featured a reward cue and a neutral cue, and the target subsequently appeared in the location of the reward cue) than on neutral-baseline trials; if attention were more likely to be captured to the location of a reward cue, then one might expect facilitation on valid trials. One interpretation of these findings is that there was therefore no effect of capture, and hence in turn that the 'invalid versus baseline 'comparison must demonstrate an effect of disengagement. However, once again drawing this conclusion requires accepting the null hypothesis ("there was no significant difference in performance on valid versus baseline trials; therefore there was no effect of capture"). This issue is particularly germane because floor effects on response time may have masked facilitation on valid trials, and also because there is no a priori reason to assume—under a capture-based account—that the magnitude of facilitation when attention was captured to the correct location (on valid trials) would be equal to the magnitude of impairment when attention was captured to the incorrect location (on invalid trials).

To summarise, on the face of it the existing literature relating to effects of reward on disengagement suggests an inconsistency: one study (Müller et al., 2016) has reported data consistent with delayed disengagement from reward cues, whereas other research (Le Pelley et al., 2015; Theeuwes & Belopolsky, 2012) has not found evidence of this effect. However, both sets of data are subject to caveats to at least some degree. The aim of the current study was therefore to provide a strong and direct test of the influence of reward on attentional disengagement. Addressing this issue is important in its own right: a better understanding of the nature of the attentional mechanisms underlying attentional bias for reward would provide insight into when and how reward-related stimuli might be expected to take and hold control of attentional processing (and hence potentially interfere with ongoing, goal-directed behaviour). Beyond this, the question may have implications for our understanding of certain clinical disorders. Attentional biases to motivationally relevant stimuli have been implicated in disorders such as addiction (bias towards reward; Albertella et al., 2017; Albertella, Watson, Yücel, & Le Pelley, 2019; Anderson, Faulkner, Rilee, Yantis, & Marvel, 2013; Christiansen, Schoenmakers, & Field, 2015) and anxiety (bias towards threat; Cisler & Koster, 2010). A better understanding of the source of such biases—whether they reflect the extent to which stimuli *pull* attention or *hold* attention—may inform the development of training-based interventions (MacLeod & Clarke, 2015; Rinck, Wiers, Becker, & Lindenmeyer, 2018; Wiers, Gladwin, Hofmann, Salemink, & Ridderinkhof, 2013) so that they are better-targeted at the root of the problem.

The current study investigated the potential influence of reward on attentional disengagement using an approach originally developed by Brockmole, Boot and colleagues (Blakely, Wright, Dehili, Boot, & Brockmole, 2012; Brockmole & Boot, 2009). Experiment 1 was based on the eye-tracking procedure used by Le Pelley et al., 2015, but crucially, on some trials the reward-signalling colour-singleton distractor appeared at a *central* location (see Fig. 1): that is, at the location participants were already fixating (and presumably attending) prior to appearance of the search display. These trials therefore required participants to disengage their attention from the central distractor in

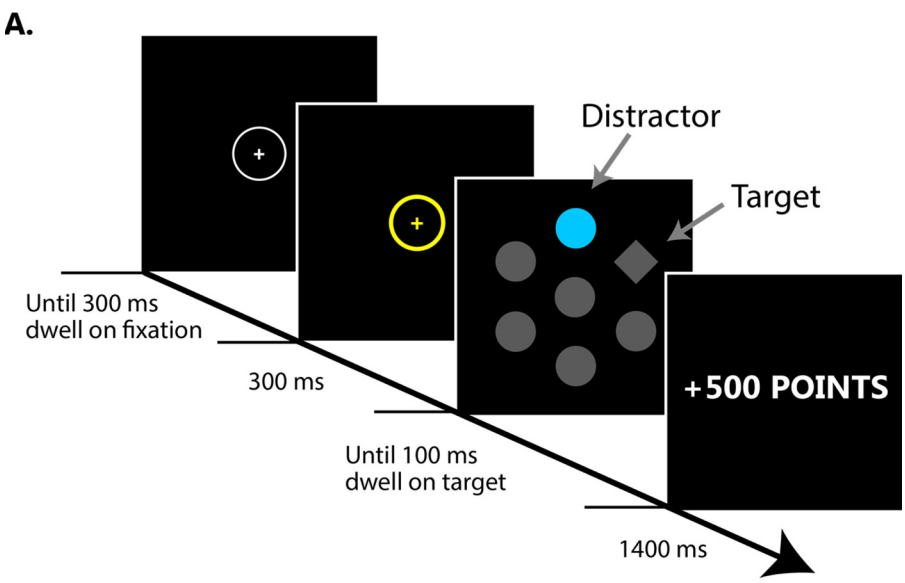

Fig. 1. A. Trial structure of the visual search task used in Experiment 1. Participants had to move their eyes to the diamond as quickly as possible on each trial. If they did so before the reward time-limit then they received either 10 or 500 points. The number of points available on each trial was signalled by the colour of the colour-singleton distractor – in this example blue signals availability of 500 points (high reward). **B.** The coloured distractor (blue or orange) could appear in one of the six outer locations or at the central location. The target (diamond) never appeared at the central location. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

order to locate and make an eye-movement to the target diamond (which on these central-distractor trials was always presented in one of the *outer* locations). By presenting the distractor at an already-attended location (cf. Müller et al., 2016), this procedure minimizes the influence of any effect of reward on spatial capture, and instead provides a relatively pure measure of the ease/speed with which attention can be shifted away from the critical distractor. The key question was whether participants would take longer to disengage from a distractor signalling availability of high reward than a distractor signalling low reward, which would demonstrate an influence of reward on attentional disengagement.

2. Experiment 1

2.1. Method

2.1.1. Participants and apparatus

All research reported in this article was approved by the UNSW Sydney Human Research Ethics Advisory Panel (Psychology). Previous studies of reward-related attentional bias using procedures similar to that used here (Failing et al., 2015; Le Pelley et al., 2015; Pearson et al., 2015) have found medium to very large effect sizes (d_z = 0.54–2.2). Thus, we tested 24 participants in the current study (12 females; age M = 19.4 years, SEM = 0.53), which gave power of .80 to detect an effect size of d_z = 0.6. Participants received course credit and a performance-related monetary bonus (M = $9.80 AUD, SEM = $0.10).

Participants were tested individually using a Tobii TX300 eye-tracker (sample rate 300 Hz), mounted on a 23-inch monitor (1920 × 1280 resolution, 60 Hz refresh rate). Participants' heads were positioned in a chinrest 60 cm from the screen. For gaze-contingent calculations, the experiment script down-sampled the data from the eye-tracker to 100 Hz. Stimulus presentation was controlled by MATLAB using Psychophysics Toolbox extensions (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). Experiment scripts and raw data for all experiments reported in this article are available via the Open Science Framework at https://osf.io/je6p5/.

2.1.2. Stimuli and design

The visual search task was based on that used by Le Pelley et al., 2015. Participants began each trial by fixating in the centre of the screen (fixation display; see Fig. 1). Once 300 ms of gaze time had accumulated in the central fixation region, the fixation cross and the surrounding circle turned yellow, indicating that the trial was about to begin. After 300 ms the search display appeared; this comprised a set of seven shapes (each 2.3 × 2.3° visual angle). Six of these shapes were distributed evenly around the centre-point of the screen, with the centre of each shape at an eccentricity of 5.1° visual angle. The seventh shape was positioned at the centre of the screen. The central shape was always a circle. Of the outer shapes, five were circles, and one was a diamond (the target). On the majority of trials, one of the circles was coloured either blue (CIE *x,y* chromaticity coordinates .192/.216) or orange (CIE x,y .493/.445), and had similar luminance (~24.5 cd/m^2). All other shapes were grey (CIE *x,y* .327/.400, luminance ~8.3 cd/m^2). We refer to the colour-singleton circle as the *distractor* to distinguish it from the other (grey) circles in the display, which we refer to as non-salient non-targets. We also included a small number of no-colour-singleton trials (all shapes rendered in grey, no colour singleton).

Participants' task was to move their eyes as quickly as possible to the diamond target: a response was registered once 100 ms of gaze dwell time had accumulated within a region of interest (diameter 3.5°

visual angle) centred on this target. The colour of the distractor circle signalled the magnitude of reward that was available on each trial. For half of participants, blue was the high-reward colour and orange was the low-reward colour; for the other half of participants this mapping was reversed. If the display contained a distractor rendered in the high-reward colour, an eye-movement to the diamond target could earn 500 points; if the display contained a distractor in the low-reward colour (or no colour-singleton), a response could earn only 10 points. The trial ended immediately when a response was registered, or after 2000 ms (timeout).

Whether participants earned the available reward on each trial depended on whether their response time (RT: the time from onset of the search display to the point at which 100 ms of dwell time had accumulated on the target) was less than the *reward time-limit* for the current block of trials. For all participants the reward time-limit during the first block was 1500 ms. From the second block onwards, the reward time-limit was the 75th percentile of recorded RTs from the previous block. If RT on a given trial was less than the reward time-limit for that trial, the participant earned a reward, with a feedback screen showing the number of points earned (either 10 or 500 points, as specified above). If RT was greater than the reward time-limit or if no response was registered before the timeout, the feedback "Too slow: +0 points. You could have won [10/500] points" appeared as appropriate.[1]

Each block consisted of 70 trials. Sixty of these trials featured a colour-singleton distractor. In half of these distractor-present trials, the singleton distractor appeared in the central location; in the other half, the distractor appeared in one of the six outer locations (see Fig. 1B). Within each of these sets of trials (central-distractor and outer-distractor), in half of trials the distractor was rendered in the high-reward colour, and in the other half it was rendered in the low-reward colour. The remaining 10 trials of each block were no-colour-singleton trials. The target never appeared in the central location. Within these constraints, the locations of the target and singleton-distractor (if one was present) were chosen randomly on each trial.

2.1.3. Procedure

Participants were informed that their task was to move their eyes to the diamond "as quickly and directly as possible", and that they would receive a monetary bonus ("typically $8 to $13") at the end of the experiment, depending on how many points they earned; no other information on the conversion rate between points and money was provided. Participants were then instructed on the colour–reward contingencies in the visual search task, e.g., that whenever a blue circle was present in the display, they could win 500 points for looking at the diamond, and whenever an orange circle was present, they could win 10 points. Participants were also informed that they would only win the points if they moved their eyes to the diamond quickly, and that this would get more difficult in each block. Participants completed 6 blocks (420 trials) in total and took a short break between blocks.

2.1.4. Data analysis

Data analysis followed our previous protocols using similar procedures (Le Pelley et al., 2015; Pearson et al., 2016). We discarded the data from the first two trials of each block, trials which timed-out before a response was recorded (0.8% of all trials), and trials with less than 25% valid gaze location data (0.2% of all trials). Our primary measures of interest were the latency and direction of the first saccade made after onset of the search display, for each of the different trial types. A velocity-threshold identification algorithm (Salvucci & Goldberg, 2000) was used to detect saccades with a velocity criterion of 40° visual angle per second (using the raw data from the eye tracker sampled at 300 Hz, rather than the down-sampled data used for gaze-contingent control of stimulus presentation). As in our previous work (Le Pelley et al., 2019; Pearson et al., 2016), a saccade was defined as going in the direction of a stimulus if its angular deviation was less than 30° to the left or right of the location of the centre of that stimulus. Trials were excluded from the saccade analysis if the participant made an anticipatory saccade (defined as a saccade latency below 80 ms), the start point of the saccade was more than 100 pixels from the centre of the screen, or if there was insufficient eye-gaze data to identify a saccade. Two participants had more than 20% of their trials discarded according to these criteria and so were excluded from the saccade analysis. For the remaining 22 participants, 7% of total trials were discarded.

Our primary interest in this study was the influence of reward on performance. Hence our analyses focused on the contrast between trials with a high-reward distractor, and trials with a low-reward distractor. This allows us to isolate the effect of reward, since in both cases the search display featured a colour-singleton distractor—the only difference being the size of reward that the distractor signalled. All raw data (including data from no-colour-singleton trials, which are not analysed here as they do not relate to our central question) are available at https://osf.io/je6p5/.

For central-distractor trials, the target (a shape singleton) was the only salient stimulus in the display outside the fixation region. For these trials, our primary focus was the proportion and latency of first saccades that were directed towards the target, as a function of signalled reward (high vs low reward). For outer-distractor trials there were two salient stimuli in the display that participants might saccade to: the (shape-singleton) target and the (colour-singleton) distractor. Initial analysis of outer-distractor trials therefore examined the proportion of first saccades directed towards either the target or the distractor as a function of signalled reward (high vs low reward). We then used repeated-measures ANOVA to investigate the latency of these first saccades as a function of direction (towards target vs distractor) and signalled reward. Finally, in order to assess the negative consequences of reward-related attentional bias—through RT slowing leading to lost rewards—we examined the proportion of trials on which participants received reward (either 500 points or 10 points as appropriate): that is, trials on which the response was faster than the reward time-limit. These data were analysed using repeated measures ANOVA with factors of distractor location (central vs outer) and signalled reward. We performed follow-up contrasts to explore significant effects. Where assumptions of sphericity were violated, Greenhouse-Geisser *p*-values are reported with the original degrees of freedom.

2.2. Results

2.2.1. Saccade analysis: central-distractor trials

We examined the direction and latency of first saccades on central-distractor trials as a function of signalled reward (high vs low reward). Unsurprisingly, given that the target was the only salient stimulus in the display outside the fixation region, the proportion of first saccades directed towards the target was high on both high-reward trials (M = .80, SEM = .03) and low-reward trials (M = .78, SEM = .03), with no significant difference between conditions, $t(21) = 1.29$, $p = .212$, $d_z = .18$. Importantly, analysis of the latencies of these saccades-to-target on central-distractor trials (Fig. 2A) revealed that participants were significantly slower to initiate a saccade away from the high-reward distractor relative to the low-reward distractor, $t(21) = 4.63$, $p < .001$, $d_z = .37$, indicating delayed disengagement from the high-reward

[1] Unlike in Le Pelley et al.'s (2015) previous study, in the current procedure looking at the colour-singleton distractor did not lead to omission of the reward. We could not practically implement this reward-omission criterion here: since participants began central-distractor trials looking at the distractor, doing so would have made it impossible to earn reward on these trials. Nevertheless, the time pressure for making a rapid eye movement to the target in the current procedure (slow responses were not rewarded) should have encouraged participants to saccade to the target as quickly and as directly as possible (see: Le Pelley, Pearson, Porter, Yee, & Luque, 2019).

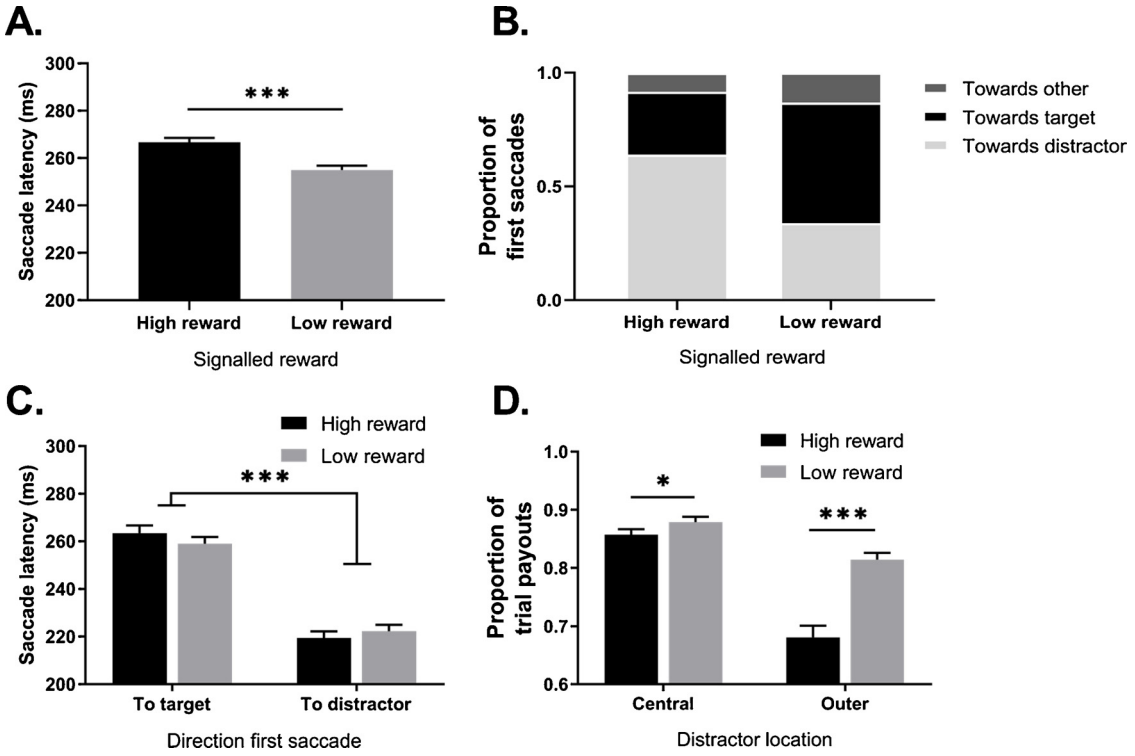

Fig. 2. Data from Experiment 1. **A.** Central-distractor trials: Latency of first saccades (directed towards the target) for trials featuring a high- or low-reward distractor presented in the central location. **B.** Outer-distractor trials: Proportion of first saccades going in the direction of the target, the distractor, or towards one of the non-salient non-target grey circles (labelled 'other'). **C.** Saccade latency on outer-distractor trials, as a function of saccade direction (towards target or distractor) and signalled reward (high vs low reward). **D.** Proportion of trial payouts, i.e., trials on which participants' response time was below the reward time-limit and hence reward was earned (500 points or 10 points, as appropriate). Data are shown separately for trials in which the distractor appeared at a central versus an outer location, and as a function of whether the colour of the distractor signalled the availability of high or low reward. *** $p < .001$. Error bars represent within-subject standard error of the mean (Cousineau, 2005) with Morey correction (Morey, 2008).

distractor.

2.2.2. Saccade analysis: outer-distractor trials

On outer-distractor trials, participants' first saccade was significantly more likely to go in the direction of the high-reward distractor versus the low-reward distractor, $t(21) = 6.55$, $p < .001$, $d_z = 1.4$ (see Fig. 2B). Correspondingly, the first saccade was less likely to go towards the target on trials with a high-reward distractor, $t(21) = 5.97$, $p < .001$, $d_z = 1.24$. We next analysed latency of the first saccade as a function of saccade direction (towards the target or the colour-singleton distractor) and signalled reward (high reward vs low reward): see Fig. 2C. Data from one participant were excluded from this analysis as this participant never made a first saccade towards the target on low-reward trials with an outer distractor. For the remaining participants, ANOVA revealed a main effect of direction, with saccades towards the distractor emitted (on average) more rapidly than those towards the target, $F(1,20) = 90.1$, $p < .001$, $\eta_p^2 = .82$. Although there was a significant interaction between direction and signalled reward, $F(1,20) = 4.41$, $p = .049$, $\eta_p^2 = .18$, follow-up tests did not reveal a significant effect of signalled reward on saccade latencies directed towards either the target, $t(20) = 1.41$, $p = .174$, $d_z = .15$, or the distractor, $t(20) = 1.47$, $p = .156$, $d_z = .20$.

2.2.3. Dwell time analysis: outer-distractor trials

As mentioned earlier, previous studies that included only outer-distractor trials have used the duration of gaze dwell-time on reward-related distractors to index attentional disengagement (Le Pelley et al., 2015; Theeuwes & Belopolsky, 2012) – a measure that we have argued is likely to be insensitive. For completeness, we derived the same measure for the current data: for the subset of outer-distractor trials on which participants registered any gaze on the reward-related distractor, we calculated the duration for which gaze remained on this distractor. While there was a trend in the direction of longer dwell time on high-reward distractors ($M = 121$ ms, $SEM = 7$ ms) than on low-reward distractors ($M = 113$ ms, $SEM = 6$ms), this did not reach significance $t(23) = 1.73$, $p = 0.098$, $d_z = .35$.

2.2.4. Proportion of trial payouts

Fig. 2D shows the proportion of trials on which participants received reward (either 10 points or 500 points as appropriate), as a function of distractor location (central vs outer) and signalled reward. ANOVA revealed a main effect of distractor location, $F(1,21) = 61.3$, $p < .001$, $\eta_p^2 = .72$, with participants performing better (receiving more rewards) for central-distractor trials than outer-distractor trials: central-distractor trials were easier by virtue of the target being the only salient item in the outer display. There was also a significant main effect of signalled reward, $F(1,21) = 34.0$, $p < .001$, $\eta_p^2 = .60$, with a lower proportion of trial payouts on trials with a high-reward distractor versus a low-reward distractor. These main effects were qualified by a significant interaction between distractor location and signalled reward, $F(1,23) = 24.6$, $p < .001$, $\eta_p^2 = .52$, with a greater effect of signalled reward for outer-distractor trials than central-distractor trials. However, pairwise contrasts revealed that the effect of signalled reward—fewer payouts for trials with high-reward versus low-reward distractors—was significant for both central-distractor trials, $t(23) = 2.28$, $p = .032$, $d_z = .50$, and outer-distractor trials, $t(23) = 5.86$, $p < .001$, $d_z = 1.47$.

2.3. Discussion

In Experiment 1 we used eye-tracking to investigate the effect of reward magnitude on attentional processes. Specifically, we examined

whether a distractor predictive of high reward relative to low reward would not only capture attention more frequently but also lead to delayed disengagement of attention, under conditions where participants were motivated to move their eyes quickly to a target. Critically, Experiment 1 included trials in which the reward-signalling distractor appeared at the central (fixation) location, therefore requiring participants to first disengage attention from this distractor before making a saccade to the target. On these central-distractor trials participants were slower to initiate the first saccade when the distractor was rendered in the high-reward colour relative to the low-reward colour. This finding suggests that reward influences the process of attentional disengagement: high-reward-signalling distractors are more likely to hold attention at their location. When the distractors were presented in outer locations, away from the central fixation point, we found that participants' initial saccades were more likely to be in the direction of the distractor (as opposed to the target) when the distractor signalled the availability of high reward than when it signalled low reward. The results from outer-distractor trials replicate previous findings from similar procedures showing an influence of reward associations on the likelihood of attentional capture by reward-signalling distractors (Failing et al., 2015; Le Pelley et al., 2015; Pearson et al., 2015). For the subset of outer-distractor trials in which participants' gaze was captured by the reward-related distractor, there was a trend in the direction of gaze subsequently lingering for longer on the high-reward distractor than the low-reward distractor; however, this trend did not reach significance. This failure to find a significant difference in distractor dwell-time on outer-distractor trials replicates previous findings (Le Pelley et al., 2015; Theeuwes & Belopolsky, 2012). As we noted in the introduction, the approach of examining duration of dwell following capture is likely to be an insensitive measure of influences on attentional (dis)engagement. The results of Experiment 1 underscore this issue: while distractor-dwell data from outer-distractor trials provided only trend-level evidence of an influence of reward on disengagement, the more sensitive analysis of central-distractor trials revealed a highly significant effect.

Notably the greater capture by, and delayed disengagement from, high-reward distractors that we observed in Experiment 1 was counterproductive to participants' goal of earning reward. Participants received the available reward on each trial (10 or 500 points) only if they moved their eyes to the diamond target quickly. Hence the longer attention lingered on the distractor, the lower the likelihood that reward would be earned. Consistent with this idea, participants received significantly fewer (large) reward payouts on trials with a high-reward distractor than (small) payouts on trials with a low-reward distractor; and this pattern was observed on both outer-distractor and central-distractor trials.

3. Experiment 2

In Experiment 2 we sought to replicate the finding of delayed disengagement from high-reward-signalling distractors using a variant of the visual search task in which the critical measure was RT to make a manual response based on the identity of the target, rather than eye gaze (see e.g., Le Pelley et al., 2015, Experiment 2). In this procedure, greater RT on trials with a high-reward central distractor (versus a low-reward central distractor) would indicate an influence of reward on attentional disengagement – the longer attention lingered on the central distractor, the slower participants would be to identify and respond to the target. In particular, Experiment 2 investigated whether reward would still influence disengagement from a central location under conditions in which the reward-signalling distractor only appeared at this central location (and never in one of the outer locations). Under these conditions, participants could in principle learn to suppress attention to the central location and instead focus on locating the target among the outer locations (Leber, Gwinn, Hong, & O'Toole, 2016; Maljkovic & Nakayama, 1996; Wang et al., 2019).

3.1. Method

3.1.1. Participants and apparatus

Experiment 2 was run as part of a practical class for second-year Psychology students at UNSW Sydney: participants were unaware of the aims of the study and had not been taught about this research topic prior to participating. A total of 238 students completed the study in their own time.[2] Sixteen participants were excluded from all analyses (see Results section), giving a final sample size of $N = 222$. The task was programmed in Inquisit 5 and delivered over the internet: participants completed the experiment using personal computers (the task was not compatible with tablets or smart phones). Inquisit scripts are able to access high-performance native system components on the local machine in order to achieve millisecond-precision timing.

3.1.2. Stimuli and design

The visual search task was based on that used by Le Pelley et al., 2015, Experiment 2). Each trial began with a central fixation cross, which participants were instructed to fixate. After a random interval of 500–700 ms, the cross disappeared and was followed by a blank screen for 150 ms, after which the search display appeared. This search display was similar to that used in Experiment 1, except that now all shapes were outlines, and each contained a white line segment (see Fig. 3A). The line inside the diamond target was oriented horizontally or vertically, selected at random on each trial; all other shapes contained a line tilted 45° degrees randomly to the left or right.

Participants' task was to respond to the orientation of the line within the diamond target as quickly as possible, by pressing 'C' (horizontal) or 'M' (vertical). The faster participants made a correct response, the more points they earned. On the majority of trials, a colour-singleton circle (the distractor) appeared at the central location. The colour of this distractor (orange or blue) indicated whether the current trial was a high- or low-reward trial, with assignment of colours to high- or low-reward roles counterbalanced across participants. On trials with a low-reward central distractor (or no-colour-singleton trials in which all shapes were grey), correct responses earned 1 point for every 10 ms that RT was below 1000 ms (e.g., an RT of 650 ms would earn 35 points). Trials with a high-reward distractor were labelled as "bonus trials", and points were multiplied by 10 (e.g., RT of 650 ms would earn 350 points). Correct responses with RT > 1000 ms and incorrect responses earned no points. The search display remained on-screen until the participant responded or the trial timed-out (after 2000 ms). A feedback screen then appeared. If the response was correct, feedback showed the number of points earned on that trial; if the response was incorrect, feedback was "Error, 0 points"; and if the trial timed-out or RT was greater than 1000 ms, feedback was "TOO SLOW: Please try to respond faster". On bonus (high-reward) trials feedback was accompanied by the text "10 × bonus trial!". On all trials the feedback screen also showed the total number of points earned so far.

Each block consisted of 40 trials. Thirty-two of these trials featured a colour-singleton distractor, presented at the central location – in half of these trials the distractor was rendered in the high-reward colour, and in the other half it was rendered in the low-reward colour. The remaining eight trials of each block were no-colour-singleton trials (all shapes were grey). The target occurred randomly at one of the six outer locations, and never appeared in the central location.

3.1.3. Procedure

Our ethical approval did not allow us to give monetary bonuses, since participants completed this study as part of their coursework.

[2] We accidentally omitted to collect demographic information in Experiments 2 and 3. In the previous year, of 398 students who were taking the same course, 70% were female and mean age was 20.66 (SEM = .18) years. The participant samples of Experiments 2 and 3 presumably had a similar demographic profile.

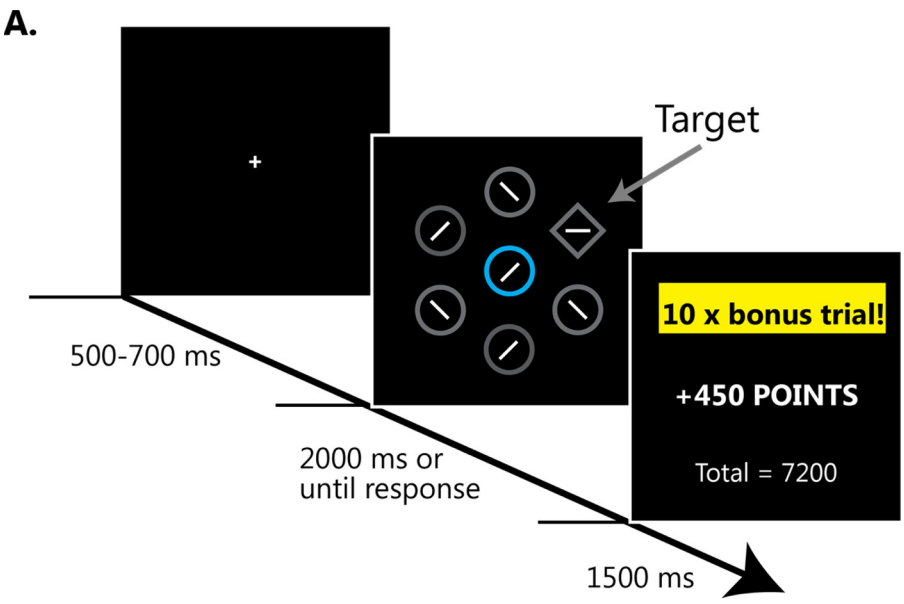

Fig. 3. A. Trial structure of the visual search task used in Experiments 2 and 3. Participants' task was to indicate with a key press whether the line inside the diamond target was oriented vertically or horizontally. The faster participants responded (correctly) the more points they earned. The search display could contain a colour-singleton shape (here a blue circle); the colour of this shape signalled whether this was a bonus trial on which points were multiplied by 10. **B.** On central-distractor trials (Experiments 2 and 3), the colour-singleton shape was a circle distractor which appeared at the central location, and the target diamond appeared in one of the outer locations. On central-target trials (Experiment 3 only), the colour-singleton shape was the target, which appeared at the central location; all of the circles were grey. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Instead participants were instructed that their task was to earn as many points as possible in order to unlock 'expertise medals' (see also Albertella et al., 2019). For every 6000 points that they earned they unlocked another medal (in the order bronze, silver, gold, platinum, diamond, and elite); based on pilot data, this conversion rate was set so that the best performing ~10% of participants would unlock the 'elite' medal.

Participants were informed that (1) faster (correct) responses would earn more points, (2) when a circle in the high-reward colour appeared in the search display it would be a bonus trial on which points were multiplied by 10, and (3) when a circle in the low-reward colour appeared it would not be bonus trial. Check-questions verified that participants understood these instructions. Participants then completed eight blocks (320 trials) with a break between each block in which their current expertise medal was revealed.

3.2. Results

We excluded all trials where response time was faster than 150 ms or slower than 1000 ms. Sixteen participants who had more than 25% of trials excluded based on these criteria, or whose mean response accuracy was below 50% correct (chance level), were excluded from all analyses.

Our primary interest was in how participants' speed of responding to the target was influenced by the reward-signalling status of the coloured distractor in the search display, i.e., the difference in mean RT (calculated for correct responses only) on trials with a high-reward distractor versus trials with a low-reward distractor. This provides our index of the effect of reward on attentional disengagement. Critically, a paired *t*-test revealed that RT for high-reward distractor trials (M = 624 ms, SEM = 4 ms, within-subjects SEM [$wSEM$: Morey, 2008] = .85 ms) was significantly greater than for low-reward distractor trials (M = 615 ms, SEM = 4 ms, $wSEM$ = .85 ms), $t(221) = 7.72$, $p < .001$, $d_z = .52$. This difference in RT did not reflect a speed–accuracy trade off: secondary analysis revealed that response accuracy was significantly lower on high-reward distractor trials (M = 84.7% SEM = 0.6%, $wSEM$ = 0.18%) than low-reward distractor trials (M = 85.3%, SEM = 0.5%, $wSEM$ = 0.18%), $t(221) = 2.15$, $p = .033$, $d_z = .14$.

3.3. Discussion

Using an online version of the visual search task based on RT rather than eye gaze, Experiment 2 demonstrated that participants were slower (and less accurate) to respond to the search target when the centrally located distractor signalled high reward relative to low reward. This result provides a conceptual replication of the critical finding from the central distractor trials of Experiment 1, and once again suggests that participants are slower to disengage attention from a distractor that has previously signalled the availability of high reward (relative to low reward). Once again, this pattern of performance was counterproductive, in that slower and less accurate responses corresponded to rewards (points) being foregone. Unlike in Experiment 1,

the distractor *always* appeared at the central location in Experiment 2. Thus, even when participants knew in advance where the colour-singleton distractor would appear, they were unable to prevent the counterproductive influence of this distractor on performance. To the extent that participants were able to suppress attention to this central location (Leber et al., 2016; Maljkovic & Nakayama, 1996; Wang et al., 2019), this suppression was insufficient to overcome the effect of reward.

To summarise, Experiments 1 and 2 provided evidence of slower responding on central-distractor trials when the distractor signalled availability of high reward, than when it signalled low reward – a finding that is consistent with delayed attentional disengagement from high-reward-signalling stimuli. There is, however, potentially an alternative, non-attentional explanation. It is possible that a signal of high reward might cause a general slowdown in performance by causing "behavioural freezing" (Müller et al., 2016), much as has been observed in response to signals of threat (Clarke et al., 2013). If a high-reward stimulus presented at fixation freezes participants for a short time—effectively pausing any ongoing behaviour—then this would manifest in slower responding on these trials: participants would take longer to start moving their eyes (cf. Experiment 1) or to locate and respond to the target (cf. Experiment 2). By contrast, the account based on attentional disengagement sees the high-reward distractor as holding attention (specifically) for longer, but not freezing behaviour in general.

4. Experiment 3

Experiment 3 was designed to discriminate between these alternatives (attentional disengagement versus behavioural freezing). Experiment 3 was closely based on Experiment 2 but included trials in which the target appeared at the central location. Furthermore, on these *central-target* trials, the target could appear in either the high-reward or low-reward colour. If the presence of a high-reward colour in the search display causes general behavioural freezing, then participants should be slower to respond to the target on central-target trials with a high-reward colour than with a low-reward colour, just as they are slower for central-distractor trials with a high-reward versus a low-reward distractor. In both cases, the behavioural freezing account anticipates that the high-reward colour will slow down ongoing behaviour. If instead participants are slower to disengage attention from high-reward-signalling stimuli, then we expect a different pattern of behaviour on central-distractor and central-target trials. On this account, participants will respond *slower* on central-distractor trials with a high-reward distractor versus a low-reward distractor (as in Experiment 2), because they must disengage attention from the central distractor in order to locate and respond to the target. By contrast, participants will (if anything) respond *faster* on central-target trials with a high-reward versus a low-reward target, because the high-reward colour will be more likely to hold attention at the target location, enhancing processing of this target and hence allowing for faster identification of the correct response.

4.1. Method

4.1.1. Participants

Participants were 220 second-year UNSW Psychology students who completed the study over the internet (none of these participants had previously completed Experiment 1 or 2). Nineteen participants were excluded from all analyses (see Results section), leaving a final sample size of $N = 201$.

4.1.2. Stimuli, design and procedure

The visual search task was similar to that of Experiment 2. The only difference was that Experiment 3 also included central-target trials, in which the target appeared in the central location and the six outer locations held grey circles (see Fig. 3b). On these central-target trials, the target could appear in the high-reward colour, the low-reward colour, or grey. If the search display contained a shape rendered in the high-reward colour (regardless of whether this was a distractor or target), the trial was a bonus trial on which points earned for a correct response were multiplied by 10.

Participants completed eight blocks of 40 trials each. Half of the trials in each block were central-target trials, and the other half were central-distractor trials (these central-distractor trials were as in Experiment 2). For each type of trial—central-target and central-distractor—on 8 trials the central shape appeared in the high-reward colour, on 8 trials in the low-reward colour, and on 4 trials in grey (no colour singleton).

4.2. Results

As in Experiment 2, we excluded all trials where response time was faster than 150 ms or slower than 1000 ms. Nineteen participants who had more than 25% of trials excluded based on these criteria, or whose mean response accuracy was below 50% (chance level), were excluded from all analyses.

Our primary interest was in how participants' speed of responding to the target was influenced by the reward-signalling status of the central coloured shape in the search display, and whether this influence of reward depended on whether the central shape was a distractor or the target. We therefore analysed mean RT (for correct responses) as a function of central stimulus (target vs distractor) and signalled reward (high reward vs low reward), using repeated measures ANOVA (see Fig. 4A). This revealed a significant main effect of central stimulus, F

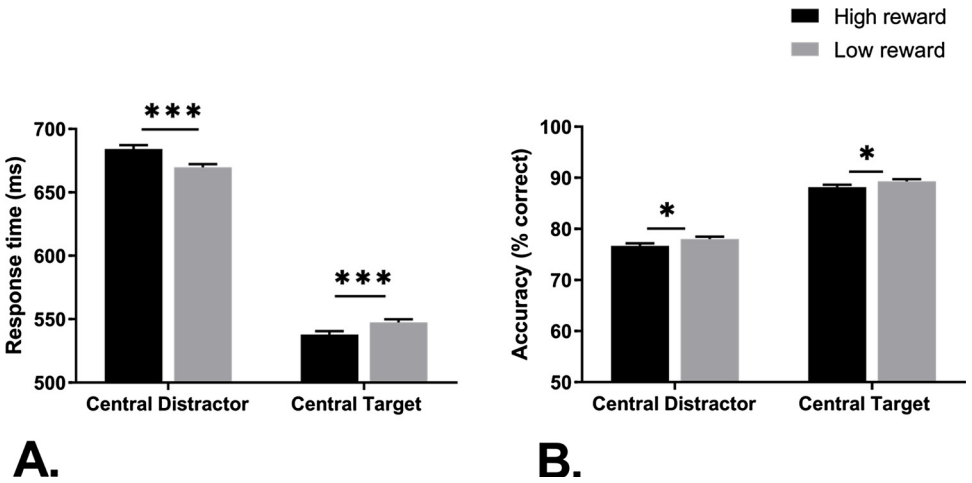

Fig. 4. Data from Experiment 3. **A.** Response time for correct responses. **B.** Response accuracy. Data are shown separately for trials in which the central stimulus was a distractor or a target, and for trials in which this central shape was rendered in a colour that signalled availability of high or low reward. * $p < .05$, *** $p < .001$. Error bars represent within-subject standard error of the mean (Cousineau, 2005) with Morey correction (Morey, 2008).

(1,200) = 1016.8, $p < .001$, $\eta_p^2 = .84$, with faster responses on central-target trials than central-distractor trials. There was also a marginally significant main effect of signalled reward, $F(1,200) = 3.89$, $p = .050$, $\eta_p^2 = .02$, superseded by an interaction between signalled reward and central stimulus, $F(1,200) = 76.2$, $p < .001$, $\eta_p^2 = .28$. Planned pairwise comparisons revealed that, for central-distractor trials, responses were significantly slower on high-reward relative to low-reward trials, $t(200)$ 6.39, $p < .001$, $d_z = .45$. By contrast, for the central-target trials responses were significantly *faster* on high-reward relative to low-reward trials, $t(200) = 6.94$, $p < .001$, $d_z = .49$.

A secondary analysis explored response accuracy (Fig. 4B). Here ANOVA revealed a significant main effect of central stimulus, $F(1,200) = 286.8$, $p < .001$, $\eta_p^2 = .59$, with more accurate responding on central-target trials than central-distractor trials. There was also a significant main effect of signalled reward, $F(1,200) = 13.8$, $p = .001$ $\eta_p^2 = .07$: overall, participants were more accurate on low-reward than high-reward trials. The interaction was not significant, $F < 1$, $p = .88$, $\eta_p^2 < .001$. Planned pairwise contrasts revealed that the effect of signalled reward was significant for central-distractor trials, $t(200) = 2.51$, $p = .013$, $d_z = .18$ and central-target trials, $t(200) = 3.03$, $p = .003$, $d_z = .22$.

The above analyses revealed that, on central-target trials, faster responding to high-reward targets was accompanied by lower accuracy (see Fig. 4); the difference in accuracy was numerically small, but significant. This pattern could be taken to suggest some degree of speed-accuracy trade-off on these trials. To examine this further, we computed inverse efficiency (IE: Townsend & Ashby, 1978, 1983) for the central-target trials. By dividing the latencies of correct responses by the proportion of correct responses, the IE score weights response time by accuracy and provides a useful summary of both pieces of information (Bruyer & Brysbaert, 2011). Analysis of the central-target trials revealed that the IE score did not differ significantly between the high-reward ($M = 616$ ms, $SEM = 7$ ms) and low-reward trials ($M = 618$ ms, $SEM = 7$ ms), $t(200) = 0.67$, $p = .506$, $d_z = 0.05$. In order to quantify support for the null hypothesis that IE did not differ between high- and low-reward central-target trials, we conducted a Bayesian paired *t*-test using JASP (JASP Team, 2018) using the default Cauchy prior. This yielded strong evidence in favour of the null over the (two-tailed) alternative hypothesis that IE scores differed as a function of reward value, $BF_{01} = 10.2$, error < .001%, and yet stronger evidence in favour of the null versus the one-tailed alternative hypothesis (based on the idea of behavioural freezing) that IE scores would be greater for high-reward trials than low-reward trials, $BF_{01} = 20.0$, error < .001%.

4.3. Discussion

Experiment 3 found once again that participants' responses were slower (and less accurate) on trials where a centrally presented distractor signalled a high relative to a low reward. Critically, a very different pattern was observed for the central-target trials: here participants were significantly *faster* to respond when the colour of the central target signalled availability of high relative to low reward. This finding is inconsistent with the idea that a global 'behavioural freezing' occurs when participants encounter a signal of high reward (Clarke et al., 2013; Müller et al., 2016) as this would lead to a general *slowing* of responses in the presence of a high-reward-signalling stimulus. That said, there was some evidence of a potential speed-accuracy trade-off on central-target trials, as faster responding to high-reward targets was accompanied by lower accuracy. To examine this more closely we analysed inverse efficiency scores, which combine speed and accuracy to yield an overall performance measure. This analysis revealed no significant effect of reward magnitude on performance on central-target trials, with a Bayesian analysis yielding strong evidence in favour of the null hypothesis. This follow-up analysis again indicates that the signal of high reward did not produce behavioural freezing in this procedure. These findings in turn suggest that behavioural freezing was not the source of the impaired responding that we observed on central-distractor trials in the presence of a high-reward distractor in Experiments 1–3. Instead the findings are consistent with the idea that participants are slower to disengage attention from a high-reward-signalling stimulus, leading to slower responses on central-distractor trials (when participants must disengage attention from the reward-signalling distractor in order to respond to the target), but no impairment (and potentially facilitation) on central-target trials, since here disengagement is not required.

5. Experiment 4

In Experiments 1–3, delayed disengagement from high-reward distractors was counterproductive to task performance, in that slower responses were less likely to be rewarded with points (Experiment 1) or earned fewer points (Experiments 2 and 3). Under a goal-directed account of performance in this task, once participants had identified the colour (and hence reward status) of the stimulus presented at fixation, then they should have been faster to respond on trials in which a high reward was at stake than when a low reward was available. The finding of the opposite pattern (slower responses on high-reward than low-reward trials) on central-distractor trials of Experiments 1–3 might therefore be taken to suggest a relatively automatic effect of reward on attentional disengagement, over which participants have little voluntary control. An alternative possibility, however, is that participants may have deliberately prioritized attention to high-reward distractors on the basis of their *informational value* (cf. Gottlieb, 2012). That is, the presence of a high-reward distractor in the search display provided information that the current trial could yield a large reward, and participants may have therefore strategically prioritized attention to this stimulus in order to identify occasions on which high reward was available. This was a poor strategy to use since it would result in slower responses, and hence lower rewards, than if participants ignored the distractors. Yet it remains possible that the impaired performance on high-reward trials reflects strategic attentional selection of the high-reward distractor (based on its information value) rather than an involuntary delay in disengagement (based on its reward value).

Experiment 4 aimed to decide between these alternatives by including a final test phase in which participants they were explicitly informed that no further rewards were available. Consequently, the critical reward-related distractors no longer carried useful information regarding reward magnitude during this unrewarded test phase—participants already knew that no reward would be available on each trial—and so there was no strategic reason to attend to them. Hence if delayed attentional disengagement from high-reward distractors reflects a strategic process based on informational value, then it should immediately desist once participants are aware that rewards are no longer available. By contrast, any attentional bias towards the high-reward distractor that persisted during the unrewarded test phase would demonstrate that prior training caused changes in capture, i.e., that pairings with reward can induce a persistent change in the attentional priority of a stimulus in a way that goes beyond strategic allocation of attention based on current informational value.

5.1. Method

5.1.1. Participants and apparatus

Experiment 4 was run online, with participants recruited from Amazon Mechanical Turk. Participants were paid $5 and the top-scoring 25% of participants also received a $3 bonus. A total of 151 participants completed the study. 61 participants were excluded from all analyses (see Results section), giving a final sample size of $N = 90$ (39 females, age $M = 36.0$ years, $SEM = 9.8$).

5.1.2. Stimuli, design and procedure

The visual search task was the same as that used in Experiment 2,

with the following differences. Participants were informed at the outset that the 25% of participants who earned the most points in the task would be rewarded with a $3 bonus. Each block of the task contained 30 central-distractor trials, half of which featured a high-reward distractor, and half of which featured a low-reward distractor. In the initial *rewarded phase* of the task, participants completed 12 blocks (360 trials total), with reward feedback provided as in Experiment 2. On completing the reward phase, participants saw the following instructions: "*FROM NOW ON, THERE ARE NO MORE POINTS AVAILABLE! This means that you will not win any points for the rest of the game. Nevertheless, you should carry on responding to the orientation of the line within the diamond as quickly and accurately as possible."* Participants completed a check-question to verify that they had understood these instructions. They then completed the *unrewarded phase*, which comprised two blocks (60 trials). These trials were similar to those of the rewarded phase, except that now feedback stated only whether the preceding response had been "correct" or "incorrect": no reward information was provided (i.e., feedback did not mention points, or whether the preceding trial had been a bonus trial).

5.2. Results

As in Experiments 2 and 3, we excluded all trials where response time was faster than 150 ms or slower than 1000 ms. Sixty-one participants who had more than 25% of trials excluded based on these criteria, or whose mean response accuracy was below 50% (chance level), were excluded from all analyses.

Fig. 5A shows response times from Experiment 3. A 2 (signalled reward: high vs. low) × 2 (phase: rewarded vs. unrewarded) ANOVA revealed a significant main effect of signalled reward, $F(1,89) = 12.63$, $p < .001$, $\eta_p^2 = .12$, with an overall pattern of slower responding on high-reward trials than on low-reward trials. Critically, planned pairwise comparisons revealed that this pattern of slower responses on high-reward trials was significant in both the rewarded phase, $t(89) = 3.25$, $p = 0.02$, $d_z = .34$, and the unrewarded phase, $t(89) = 2.14$, $p = 0.035$, $d_z = .23$. The ANOVA also revealed a significant main effect of phase, $F(1,89) = 14.9$, $p < .001$, $\eta_p^2 = .14$, with faster responses during the unrewarded phase than the rewarded phase. Notably, the signalled reward × phase interaction was not significant, $F < 1$, $p = .78$, $\eta_p^2 = .001$; that is, the magnitude of slowing caused by the high-reward distractor relative to the low-reward distractor did not differ significantly in the rewarded and unrewarded phases. In order to quantify support for the null hypothesis here, for each participant we calculated the difference in response times between high- and low-reward trials. A Bayesian paired *t*-test yielded strong support for the null hypothesis that the magnitude of this high-versus-low difference did not differ between phases, versus the alternative hypothesis that the difference was greater in the rewarded phase than the unrewarded phase, $BF_{01} = 10.6$, error < .001%.

A secondary analysis explored response accuracy (Fig. 5B). Here ANOVA revealed a marginally significant main effect of signalled reward, $F(1,89) = 3.5$, $p = .063$, $\eta_p^2 = .04$, with an overall trend lower accuracy on high-reward trials than low-reward trials. Planned pairwise contrasts revealed that the effect of signalled reward was significant during the rewarded phase, $t(89) = 2.34$, $p = .021$, $d_z = .25$ but not the unrewarded phase, $t(89) = 1.11$, $p = .268$, $d_z = .12$. The ANOVA also revealed a significant main effect of phase, $F(1,89) = 21.6$, $p < .001$, $\eta_p^2 = .20$, with more accurate responding during the unrewarded phase. The signalled reward × phase interaction was not significant, $F < 1$, $p = .85$, $\eta_p^2 < .001$. Bayesian analysis revealed substantial evidence in favour of the null hypothesis that the high-versus-low difference in accuracy did not differ between phases, $BF_{01} = 7.37$, error < .001%.

5.3. Discussion

Experiment 4 found once again that participants' responses were slower, but no more accurate, on trials in which a centrally presented distractor signalled availability of a high relative to a low reward – indicating delayed disengagement from high-reward distractors. Notably, this counterproductive effect of reward on performance persisted into a subsequent unrewarded phase, in which participants were explicitly informed that rewards were no longer available. This finding suggests that the impairment caused by the high-reward distractor does not reflect participants' strategic selection of this stimulus on the basis of its informational value, as the distractors provided no information during the unrewarded phase (i.e., they were entirely task-irrelevant). Instead the results of Experiment 4 are consistent with the idea that prior experience of distractor–reward relationships influences automatic attentional prioritisation, which exerts a persistent effect on attentional (dis)engagement.

6. General discussion

In the current study, we investigated whether people's ability to disengage attention from a visual stimulus is influenced by the magnitude of reward associated with that stimulus – whether a stimulus that signals availability of high reward holds attention for longer, even if participants are motivated to shift attention away from this stimulus as rapidly as possible. In Experiment 1, participants were slower to

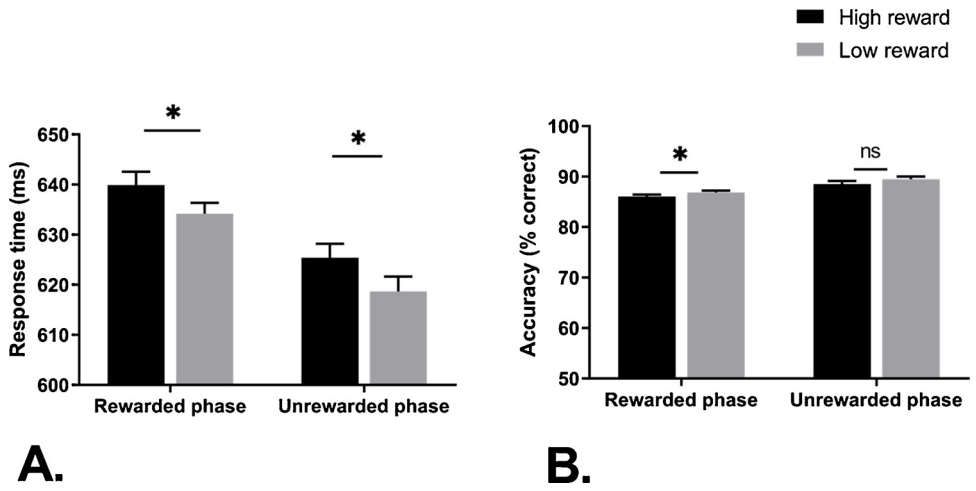

Fig. 5. Data from Experiment 4. **A.** Response time for correct responses. **B.** Response accuracy. Data are shown separately for rewarded and unrewarded phases. * $p <$ .05, ns = non-significant. Error bars represent within-subject standard error of the mean (Cousineau, 2005) with Morey correction (Morey, 2008).

move their eyes away from a colour-singleton distractor that signalled high relative to low reward when this distractor appeared at a central location. Likewise, in Experiments 2–4 participants were slower to make a manual response to a target when the search display contained a central distractor that signalled high reward (relative to low reward). Notably, the slowing on high-reward central-distractor trials did not seem to be due to a general 'behavioural freezing' (Clarke et al., 2013; Müller et al., 2016) in the presence of a high-reward-signalling stimulus, because we did not observe a similar slowing when the search display contained a central *target* rendered in the high-reward colour (Experiment 3). Across all experiments, this influence of reward on saccade/response latency was counterproductive, because slower responses meant that participants earned fewer points. In Experiment 4, we demonstrated that the effect of reward on response latency persisted into an unrewarded phase in which participants knew that no further rewards were available. That is, participants were still slower to respond when the display contained a central distractor that had previously signalled availability of high reward versus low reward, even though distractors no longer provided any information about reward availability. This demonstration of an effect of reward history on response latency under conditions where the reward-related distractors were entirely task-irrelevant indicates that learning about reward relationships exerts an automatic and involuntary influence on attention. The current results thus highlight the *conflict* that arises between goal-directed control (driving attention towards the target) and the automatic attentional prioritization of reward signals (wherein reward-signalling distractors become more likely to hold attention).

Our findings are consistent with the idea that reward magnitude modulates speed of attentional disengagement. Participants were looking at the central location when the search display appeared. On central-distractor trials, they had to disengage spatial attention from the distractor that appeared at this central location in order to locate the target. If reward influences disengagement of spatial attention, then high-reward distractors will hold attention in the central location for longer than low-reward distractors, and hence responses to the target will be delayed – as observed in Experiments 1-4. By contrast, on central-target trials (Experiment 3) maintenance of attention at the central location will (if anything) facilitate processing of the target, producing the observed pattern of faster responses on high-reward trials than low-reward trials. The current results are somewhat reminiscent of certain findings from the *attentional blink* procedure (and variants of it), which could be taken to suggest that reward-related stimuli can 'hold' cognitive processing at a particular point in time (Failing & Theeuwes, 2015; Le Pelley et al., 2017, Le Pelley, Watson, Pearson, Abeywickrama, & Most, 2018; O'Brien & Raymond, 2012; Raymond & O'Brien, 2009). Our findings go beyond this prior work to show that reward also influences the extent to which stimuli hold attention in *space*. More generally the current results are in line with the idea that cues signalling reward take on motivational salience (Robinson & Berridge, 1993, 2001) and become 'motivational magnets' from which it is difficult to disengage attention, even when it is in an observer's best interest to do so.

As noted above, delayed disengagement from high-reward distractors was counterproductive in the current experiments. In Experiments 1 and 4, it came at a financial cost, since slower responses were less likely to be rewarded with points that corresponded to a monetary bonus. Experiments 2 and 3 also revealed a significant effect of the reward-signalling status of distractors on performance, even though rewards were entirely symbolic in this task – points had no tangible monetary value. It seems that the accumulation of points per se (or the medals unlocked by these points) provided sufficient inherent motivation for effects of reward to emerge (see also Albertella et al., 2019).

In all of the experiments reported here, we manipulated whether distractors were associated with high or low reward and observed an effect of this reward manipulation on attentional disengagement. The current data do not allow us to determine whether this effect is specific to rewards per se, or whether it would extend to other motivationally significant events. For example, punishments are also motivationally significant (they will drive behaviour) but differ from rewards in their valence (rewards are positive [appetitive]; punishments are negative [aversive]). Previous research examining attentional capture has revealed parallel findings for rewards and punishments, consistent with a central role for motivational significance (e.g., Le Pelley et al., 2018; Wentura, Müller, & Rothermund, 2014; for review see: Watson, Pearson, Wiers et al., 2019): future research using the current procedure but with monetary losses instead of gains could investigate whether a similar parallel applies in the case of attentional disengagement (cf. Müller et al., 2016).

The current study contributes to a body of work examining effects of *selection history* (Awh, Belopolsky, & Theeuwes, 2012; Failing & Theeuwes, 2018) on attention, investigating how learning about the relationship between a neutral stimulus (here a colour) and reward influences attention to that stimulus. This research has parallels with a wider literature that has examined the effects of stimuli that have a pre-existing motivational status, investigating attentional bias towards drug-related stimuli (e.g., pictures of cigarettes or alcohol) in the context of addiction (see Christiansen et al., 2015; Field & Cox, 2008) and threat-related stimuli (e.g., pictures of angry faces) in the context of anxiety (see Cisler & Koster, 2010; Mulckhuyse, 2018). Notably, studies in both areas have reported evidence of biases in attentional dwell time; i.e., delayed disengagement from drug-related stimuli (e.g., Bradley, Mogg, Wright, & Field, 2003; Field, Mogg, & Bradley, 2004; Mogg, Bradley, Field, & De Houwer, 2003) and threat-related stimuli (e.g., Belopolsky, Devue, & Theeuwes, 2011; Mogg, Holmes, Garner, & Bradley, 2008; Schmidt, Belopolsky, & Theeuwes, 2017). The current finding of delayed disengagement from learned signals of reward might therefore be taken to suggest a parallel between the processes underlying attentional bias resulting from selection history, and biases observed for 'inherently' motivational stimuli that are implicated in clinical disorders (Albertella et al., 2017, 2019; Anderson et al., 2013; Anderson, 2016). However, we remain somewhat cautious in this regard, given that differences in procedures used to demonstrate effects on 'attentional disengagement' may result in those procedures tapping different processes. For example, studies of drug-related stimuli have tended to use the dot-probe task (see Introduction). When the target follows the cues at longer latencies (i.e. 2000 ms), faster responses to the target on valid trials (when it replaces the drug-related cue, e.g., a picture of alcohol) relative to invalid trials (when it replaces the control cue, e.g., a picture of a soft drink) are argued to represent a tendency for the participant to delay disengagement of attention from the drug image, relative to the control image (Bradley et al., 2003; Field et al., 2004; Mogg et al., 2003). Notably, however, under these conditions there is no strong reason *not* to attend to the drug-related cue: the target is equally likely to appear in either location and the drug image is presumably more desirable than the control image for a heavy drug-user. As such the resulting attentional bias may well reflect a strategic, goal-directed choice by the participant to maintain attention to the drug-related cue (for evidence consistent with this idea, see Preciado, Munneke, & Theeuwes, 2017). By contrast, in the current study attending to reward-distractors was counterproductive, in that the target always appeared elsewhere – and the effect of reward on disengagement persisted even when distractors were entirely task-irrelevant (Experiment 4). Our data suggest, therefore, that reward has an automatic effect, making it harder for participants to disengage attention even when they are motivated to do so. Future research could use a procedure based on the current task to shed further light on the strategic versus automatic nature of a 'disengagement bias' associated with drug- or threat-related stimuli, which could have important implications for future development and refinement of attentional-bias-retraining interventions for addiction and anxiety (Rinck et al., 2018; Wiers et al., 2013).

Finally, our findings raise the question of whether previous demonstrations of reward-related attentional bias reflect an influence of reward on attentional capture (as has often been assumed), or whether they might instead reflect delayed disengagement. Consider, for example, the outer-distractor trials of Experiment 1, in which we observed that gaze was more likely to move towards a high-reward distractor than a low-reward distractor. One interpretation of this pattern is that high-reward distractors were more likely to capture attention. An alternative possibility appeals to pre-saccadic (covert) attentional processes which allow for rapid identification of visual stimuli, prior to and in parallel with programming of eye movements (Godijn & Theeuwes, 2002). Notably, in the current study reward-related distractors were colour singletons (as in many studies of reward-related attentional bias: e.g., Anderson et al., 2011; Le Pelley et al., 2015; Pearson et al., 2015, 2016; Watson, Pearson, Chow et al., 2019), which we might expect to capture attention on the basis of their physical salience (Theeuwes, 1992). This gives rise to an alternative interpretation in which covert attention is first captured by the physically-salient colour singleton, and a saccade is then triggered to that location when attentional disengagement is slowed by reward (Godijn & Theeuwes, 2002; Müller et al., 2016). For a low-reward-signalling distractor, disengagement may be sufficiently rapid that attention is re-oriented away from the distractor before a saccade to this distractor is programmed or emitted. By contrast, on this account the high-reward-signalling distractor holds covert attention for longer, such that attention is more likely to still be at the location of the distractor when the first saccade is programmed. The findings of our central-distractor trials demonstrate that reward influences disengagement; the current data are unable to confirm whether an influence of reward on capture also contributes to the reward-related bias observed on outer-distractor trials. On this point, we note that reward-related attentional bias has also been demonstrated under conditions in which the reward-signalling stimuli are not physically salient (see: Anderson & Halpern, 2017; Failing et al., 2015; Failing & Theeuwes, 2017). However, a similar argument could still apply here: covert attention may occasionally be allocated to distractors, either randomly or because they have previously been targets of search (Anderson & Halpern, 2017), and reward may then delay disengagement from these distractors – producing the observed reward-related bias. Establishing unequivocally whether reward influences the likelihood of capture (specifically) may not be possible on the basis of existing findings, since we lack a way of reliably measuring the location of covert attention. When considering the wider clinical significance of attentional bias for reward this may be a moot point, given that reward cues tend to be physically salient by design (e.g., a neon beer logo flashing outside a bar). Nonetheless, this remains an interesting puzzle for future research in this area to solve.

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Declaration of Competing Interest

The authors declare no conflict of interest.

References

Albertella, L., Copeland, J., Pearson, D., Watson, P., Wiers, R. W., & Le Pelley, M. E. (2017). Selective attention moderates the relationship between attentional capture by signals of nondrug reward and illicit drug use. *Drug and Alcohol Dependence, 175*, 99–105. https://doi.org/10.1016/j.drugalcdep.2017.01.041.

Albertella, L., Watson, P., Yücel, M., & Le Pelley, M. E. (2019). Persistence of value-modulated attentional capture is associated with risky alcohol use. *Addictive Behaviors Reports, 10*, 100195. https://doi.org/10.1016/j.abrep.2019.100195.

Anderson, B. A. (2016). What is abnormal about addiction-related attentional biases? *Drug and Alcohol Dependence, 167*, 8–14. https://doi.org/10.1016/j.drugalcdep.2016.08.002.

Anderson, B. A., Faulkner, M. L., Rilee, J. J., Yantis, S., & Marvel, C. L. (2013). Attentional Bias for non-drug reward is magnified in addiction. *Experimental and Clinical Psychopharmacology, 21*(6), 499–506. https://doi.org/10.1037/a0034575.

Anderson, B. A., & Halpern, M. (2017). On the value-dependence of value-driven attentional capture. *Attention, Perception & Psychophysics, 79*(4), 1001–1011. https://doi.org/10.3758/s13414-017-1289-6.

Anderson, B. A., Laurent, P. A., & Yantis, S. (2011). Learned value magnifies salience-based attentional capture. *PloS One, 6*(11), 1–6. https://doi.org/10.1371/journal.pone.0027926.

Awh, E., Belopolsky, A. V., & Theeuwes, J. (2012). Top-down versus bottom-up attentional control: A failed theoretical dichotomy. *Trends in Cognitive Sciences, 16*(8), 437–443. https://doi.org/10.1016/j.tics.2012.06.010.

Belopolsky, A. V., Devue, C., & Theeuwes, J. (2011). Angry faces hold the eyes. *Visual Cognition, 19*(1), 27–36. https://doi.org/10.1080/13506285.2010.536186.

Blakely, D. P., Wright, T. J., Dehili, V. M., Boot, W. R., & Brockmole, J. R. (2012). Characterizing the time course and nature of attentional disengagement effects. *Vision Research, 56*, 38–48. https://doi.org/10.1016/j.visres.2012.01.010.

Born, S., Kerzel, D., & Theeuwes, J. (2011). Evidence for a dissociation between the control of oculomotor capture and disengagement. *Experimental Brain Research, 208*(4), 621–631. https://doi.org/10.1007/s00221-010-2510-1.

Bradley, B. P., Mogg, K., Wright, T., & Field, M. (2003). Attentional bias in drug dependence: Vigilance for cigarette-related cues in smokers. *Psychology of Addictive Behaviors, 17*(1), 66–72.

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10*(4), 433–436.

Brockmole, J. R., & Boot, W. R. (2009). Should I stay or should I go? Attentional disengagement from visually unique and unexpected items at fixation. *Journal of Experimental Psychology Human Perception and Performance, 35*(3), 808–815. https://doi.org/10.1037/a0013707.

Bruyer, R., & Brysbaert, M. (2011). Combining speed and accuracy in cognitive psychology: Is the Inverse Efficiency Score (IES) a Better Dependent Variable than the Mean Reaction Time (RT) and the Percentage Of Errors (PE)? *Psychologica Belgica, 51*(1), 5–13. https://doi.org/10.5334/pb-51-1-5.

Christiansen, P., Schoenmakers, T. M., & Field, M. (2015). Less than meets the eye: Reappraising the clinical relevance of attentional bias in addiction. *Addictive Behaviors, 44*, 43–50. https://doi.org/10.1016/j.addbeh.2014.10.005.

Cisler, J. M., & Koster, E. H. W. (2010). Mechanisms of attentional biases towards threat in anxiety disorders: An integrative review. *Clinical Psychology Review, 30*(2), 203–216. https://doi.org/10.1016/j.cpr.2009.11.003.

Clarke, P. J. F., MacLeod, C., & Guastella, A. J. (2013). Assessing the role of spatial engagement and disengagement of attention in anxiety-linked attentional bias: A critique of current paradigms and suggestions for future research directions. *Anxiety, Stress, and Coping, 26*(1), 1–19. https://doi.org/10.1080/10615806.2011.638054.

Cousineau, D. (2005). Confidence intervals in within-subject designs: A simpler solution to Loftus and Masson's method. *Tutorials in Quantitative Methods for Psychology, 1*. https://doi.org/10.20982/tqmp.01.1.p042.

Deubel, H., & Schneider, W. X. (1996). Saccade target selection and object recognition: Evidence for a common attentional mechanism. *Vision Research, 36*(12), 1827–1837.

Egeth, H. E., & Yantis, S. (1997). Visual attention: Control, representation, and time course. *Annual Review of Psychology, 48*, 269–297. https://doi.org/10.1146/annurev.psych.48.1.269.

Failing, M., Nissens, T., Pearson, D., Le Pelley, M., & Theeuwes, J. (2015). Oculomotor capture by stimuli that signal the availability of reward. *Journal of Neurophysiology, 114*(4), 2316–2327. https://doi.org/10.1152/jn.00441.2015.

Failing, M., & Theeuwes, J. (2015). Nonspatial attentional capture by previously rewarded scene semantics. *Visual Cognition, 23*(1–2), 82–104. https://doi.org/10.1080/13506285.2014.990546.

Failing, M., & Theeuwes, J. (2017). Don't let it distract you: How information about the availability of reward affects attentional selection. *Attention, Perception & Psychophysics, 79*(8), 2275–2298. https://doi.org/10.3758/s13414-017-1376-8.

Failing, M., & Theeuwes, J. (2018). Selection history: How reward modulates selectivity of visual attention. *Psychonomic Bulletin & Review, 25*(2), 514–538. https://doi.org/10.3758/s13423-017-1380-y.

Field, M., & Cox, W. M. (2008). Attentional bias in addictive behaviors: A review of its development, causes, and consequences. *Drug and Alcohol Dependence, 97*(1–2), 1–20. https://doi.org/10.1016/j.drugalcdep.2008.03.030.

Field, M., Mogg, K., & Bradley, B. P. (2004). Eye movements to smoking-related cues: Effects of nicotine deprivation. *Psychopharmacology, 173*(1–2), 116–123. https://doi.org/10.1007/s00213-003-1689-2.

Godijn, R., & Theeuwes, J. (2002). Programming of endogenous and exogenous saccades: Evidence for a competitive integration model. *Journal of Experimental Psychology Human Perception and Performance, 28*(5), 1039–1054.

Gottlieb, J. (2012). Attention, learning and the value of information. *Neuron, 76*(2), 281–295. https://doi.org/10.1016/j.neuron.2012.09.034.

Hickey, C., Chelazzi, L., & Theeuwes, J. (2010). Reward changes salience in human vision via the anterior cingulate. *Journal of Neuroscience, 30*(33), 11096–11103. https://doi.org/10.1523/JNEUROSCI.1026-10.2010.

JASP Team (2018). *JASP (Version 0.8.5)*. Retrieved fromhttps://jaspstats.org/.

Kiss, M., Driver, J., & Eimer, M. (2009). Reward priority of visual target singletons modulates event-related potential signatures of attentional selection. *Psychological Science, 20*(2), 245–251. https://doi.org/10.1111/j.1467-9280.2009.02281.x.

Kleiner, M., Brainard, D., Pelli, D., Ingling, A., Murray, R., & Broussard, C. (2007). What's new in psychtoolbox-3. *Perception, 36*(14), 1–16.

Le Pelley, M. E., Mitchell, C. J., Beesley, T., George, D. N., & Wills, A. J. (2016). Attention and associative learning in humans: An integrative review. *Psychological Bulletin,*

142(10), 1111–1140. https://doi.org/10.1037/bul0000064.
Le Pelley, M. E., Pearson, D., Griffiths, O., & Beesley, T. (2015). When goals conflict with values: Counterproductive attentional and oculomotor capture by reward-related stimuli. *Journal of Experimental Psychology: General, 144*(1), 158–171. https://doi.org/10.1037/xge0000037.
Le Pelley, M. E., Pearson, D., Porter, A., Yee, H., & Luque, D. (2019). Oculomotor capture is influenced by expected reward value but (maybe) not predictiveness. *The Quarterly Journal of Experimental Psychology, 72*, 168–181. https://doi.org/10.1080/17470218.2017.1313874.
Le Pelley, M. E., Seabrooke, T., Kennedy, B. L., Pearson, D., & Most, S. B. (2017). Miss it and miss out: Counterproductive nonspatial attentional capture by task-irrelevant, value-related stimuli. *Attention, Perception & Psychophysics, 79*(6), 1628–1642. https://doi.org/10.3758/s13414-017-1346-1.
Le Pelley, M. E., Watson, P., Pearson, D., Abeywickrama, R. S., & Most, S. B. (2018). Winners and losers: Reward and punishment produce biases in temporal selection. *Journal of Experimental Psychology Learning, Memory, and Cognition, 45*, 822–833. https://doi.org/10.1037/xlm0000612.
Leber, A. B., Gwinn, R. E., Hong, Y., & O'Toole, R. J. (2016). Implicitly learned suppression of irrelevant spatial locations. *Psychonomic Bulletin & Review, 23*(6), 1873–1881. https://doi.org/10.3758/s13423-016-1065-y.
MacLeod, C., & Clarke, P. J. F. (2015). The attentional bias modification approach to anxiety intervention. *Clinical Psychological Science, 3*(1), 58–78. https://doi.org/10.1177/2167702614560749.
Maljkovic, V., & Nakayama, K. (1996). Priming of pop-out: II. The role of position. *Perception & Psychophysics, 58*(7), 977–991. https://doi.org/10.3758/BF03206826.
Mogg, K., Bradley, B. P., Field, M., & De Houwer, J. (2003). Eye movements to smoking-related pictures in smokers: Relationship between attentional biases and implicit and explicit measures of stimulus valence. *Addiction, 98*(6), 825–836.
Mogg, K., Holmes, A., Garner, M., & Bradley, B. P. (2008). Effects of threat cues on attentional shifting, disengagement and response slowing in anxious individuals. *Behaviour Research and Therapy, 46*(5), 656–667. https://doi.org/10.1016/j.brat.2008.02.011.
Morey, R. D. (2008). Confidence intervals from normalized data: A correction to Cousineau (2005). *Tutorials in Quantitative Methods for Psychology, 4*, 61–64.
Mulckhuyse, M. (2018). The influence of emotional stimuli on the oculomotor system: A review of the literature. *Cognitive, Affective & Behavioral Neuroscience, 18*(3), 411–425. https://doi.org/10.3758/s13415-018-0590-8.
Müller, S., Rothermund, K., & Wentura, D. (2016). Relevance drives attention: Attentional bias for gain- and loss-related stimuli is driven by delayed disengagement. *The Quarterly Journal of Experimental Psychology, 69*(4), 752–763. https://doi.org/10.1080/17470218.2015.1049624.
Noudoost, B., Chang, M. H., Steinmetz, N. A., & Moore, T. (2010). Top-down control of visual attention. *Current Opinion in Neurobiology, 20*(2), 183–190. https://doi.org/10.1016/j.conb.2010.02.003.
O'Brien, J. L., & Raymond, J. E. (2012). Learned predictiveness speeds visual processing. *Psychological Science, 23*(4), 359–363. https://doi.org/10.1177/0956797611429800.
Pearson, D., Donkin, C., Tran, S. C., Most, S. B., & Le Pelley, M. E. (2015). Cognitive control and counterproductive oculomotor capture by reward-related stimuli. *Visual Cognition, 23*(1–2), 41–66. https://doi.org/10.1080/13506285.2014.994252.
Pearson, D., Osborn, R., Whitford, T. J., Failing, M., Theeuwes, J., & Le Pelley, M. E. (2016). Value-modulated oculomotor capture by task-irrelevant stimuli is a consequence of early competition on the saccade map. *Attention, Perception & Psychophysics, 78*(7), 2226–2240. https://doi.org/10.3758/s13414-016-1135-2.
Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10*(4), 437–442.
Posner, M. I., Inhoff, A. W., Friedrich, F. J., & Cohen, A. (1987). Isolating attentional systems: A cognitive-anatomical analysis. *Psychobiology, 15*(2), 107–121. https://doi.org/10.3758/BF03333099.
Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience, 13*, 25–42. https://doi.org/10.1146/annurev.ne.13.030190.000325.
Preciado, D., Munneke, J., & Theeuwes, J. (2017). Mixed signals: The effect of conflicting reward- and goal-driven biases on selective attention. *Attention, Perception & Psychophysics, 79*(5), 1297–1310. https://doi.org/10.3758/s13414-017-1322-9.
Raymond, J. E., & O'Brien, J. L. (2009). Selective visual attention and motivation: The consequences of value learning in an attentional blink task. *Psychological Science, 20*(8), 981–988. https://doi.org/10.1111/j.1467-9280.2009.02391.x.
Rinck, M., Wiers, R. W., Becker, E. S., & Lindenmeyer, J. (2018). Relapse prevention in abstinent alcoholics by cognitive bias modification: Clinical effects of combining approach bias modification and attention bias modification. *Journal of Consulting and Clinical Psychology, 86*(12), 1005–1016. https://doi.org/10.1037/ccp0000321.
Robinson, T. E., & Berridge, K. C. (1993). The neural basis of drug craving: An incentive-sensitization theory of addiction. *Brain Research Reviews, 18*(3), 247–291.
Robinson, T. E., & Berridge, K. C. (2001). Incentive-sensitization and addiction. *Addiction, 96*(1), 103–114. https://doi.org/10.1080/09652140020016996.
Salvucci, D., & Goldberg, J. (2000). *Identifying fixations and saccades in eye-tracking protocols.* 71–78. https://doi.org/10.1145/355017.355028.
Schmidt, L. J., Belopolsky, A. V., & Theeuwes, J. (2017). The time course of attentional bias to cues of threat and safety. *Cognition & Emotion, 31*(5), 845–857. https://doi.org/10.1080/02699931.2016.1169998.
Theeuwes, J. (1991). Cross-dimensional perceptual selectivity. *Perception & Psychophysics, 50*(2), 184–193. https://doi.org/10.3758/BF03212219.
Theeuwes, J. (1992). Perceptual selectivity for color and form. *Perception & Psychophysics, 51*(6), 599–606.
Theeuwes, J., & Belopolsky, A. V. (2012). Reward grabs the eye: Oculomotor capture by rewarding stimuli. *Vision Research, 74*, 80–85. https://doi.org/10.1016/j.visres.2012.07.024.
Theeuwes, J., Kramer, A. F., Hahn, S., & Irwin, D. E. (1998). Our eyes do not always go where we want them to go: Capture of the eyes by new objects. *Psychological Science, 9*(5), 379–385. https://doi.org/10.1111/1467-9280.00071.
Townsend, J. T., & Ashby, F. G. (1978). Methods of modeling capacity in simple processing systems. In J. Castellan, & F. Restle (Eds.). *Cognitive theory*https://doi.org/10.4324/9781315802473-14.
Townsend, J. T., & Ashby, F. G. (1983). *Stochastic modelling of elementary psychological processes.* Cambridge, U.K: Cambridge University Press.
Wang, B., Samara, I., & Theeuwes, J. (2019). Statistical regularities bias overt attention. *Attention, Perception & Psychophysics, 81*(6), 1813–1821. https://doi.org/10.3758/s13414-019-01708-5.
Watson, P., Pearson, D., Chow, M., Theeuwes, J., Wiers, R. W., Most, S. B., et al. (2019). Capture and control: Working memory modulates attentional capture by reward-related stimuli. *Psychological Science, 30*, 1174–1185. https://doi.org/10.1177/0956797619855964.
Watson, P., Pearson, D., Wiers, R. W., & Le Pelley, M. E. (2019). Prioritizing pleasure and pain: Attentional capture by reward-related and punishment-related stimuli. *Current Opinion in Behavioral Sciences, 26*, 107–113. https://doi.org/10.1016/j.cobeha.2018.12.002.
Wentura, D., Müller, P., & Rothermund, K. (2014). Attentional capture by evaluative stimuli: Gain- and loss-connoting colors boost the additional-singleton effect. *Psychonomic Bulletin & Review, 21*(3), 701–707. https://doi.org/10.3758/s13423-013-0531-z.
Wiers, R. W., Gladwin, T. E., Hofmann, W., Salemink, E., & Ridderinkhof, K. R. (2013). Cognitive Bias modification and cognitive control training in addiction and related psychopathology mechanisms, clinical perspectives, and ways forward. *Clinical Psychological Science, 1*(2), 192–212. https://doi.org/10.1177/2167702612466547.